RECENT CHANGES IN FROST DAYS AND THE FROST-FREE SEASON IN THE UNITED STATES

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Recent observed warming in the United States has resulted in a decrease in the number of frost days, an earlier date of the last-spring freeze, a later date of the first-fall frost, and a lengthening of the frost-free season for the 1948–99 period.

It has become clear from the observed record that global temperatures increased approximately 0.6°C over the twentieth century (Easterling et al. 2000). However, the warming has not been constant, and, for instance, Karl et al. (2000) showed that starting in 1880 there was a slight cooling trend until about 1910, then strong warming (0.12°C decade^{-1}) until early 1940s, and another period of slight cooling until the mid-1970s; since the mid-1970s, however, global temperatures have risen rapidly (0.2°C decade^{-1}). Global and U.S. temperatures for 1998 were the warmest since 1880 and may have been the warmest for any year in the last millennium (Mann et al. 1999).

Given these observed temperature changes, one of the major questions about potential climate changes is how extreme events might change. For example, Mearns et al. (1984) suggest that with an approximate 2°C warming in Iowa, the probability of summertime heat waves would triple; and Katz and Brown (1992) show that, statistically speaking, a change in variance is more important to the frequency of extreme events than a change in the mean. Therefore, if "extreme" is defined with the current temperature distribution, then shifting the entire distribution by raising the mean value with no change in variance will greatly impact the probability of occurrence of the extreme (Meehl et al. 2000), as does an increase in the variance with or without an increase in the mean (Katz and Brown 1992). With this in mind, the purpose of this study is to examine changes in frost days, as defined by days when the minimum temperature is below 0°C, and changes in the frost-free season for the continental United States for the latter half of the twentieth century.

Temperature extremes in the United States have been examined for only a few regions, most notably the northeastern United States. Cooter and LeDuc (1995) document an increase in the length of the frost-free season in the northeastern United States during 1950–93. DeGaetano (1996) looked at trends in how often both maximum and minimum temperatures in this region exceeded a variety of thresholds. He found a tendency toward fewer cold minimum temperature threshold exceedences, more warm minimum temperature threshold exceedences, and also fewer warm

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maximum temperature exceedences. These findings are consistent with a number of studies (Easterling et al. 1997; Karl et al. 1993) that find evidence of more warming being found in minimum (nighttime) temperatures than in maximum (daytime) temperatures. More recently, Schwartz and Reiter (2000) found phenological evidence of a move to an earlier spring in parts of North American, and Cayan et al. (2001) also found a change toward earlier spring in the western United States using both phenological and streamflow data.

Elsewhere around the globe, a few studies document changes in frost days. Frich et al. (2002) found evidence of longer growing seasons and fewer frost days in much of the mid- and high latitudes in the Northern Hemisphere in the last 50 years. Furthermore, Heino et al. (1999) found decreasing frost days across northern Europe during the twentieth century, and similarly, Bonsal et al. (2001) also found decreasing frost days in Canada.

METHODS AND RESULTS. There are a variety of definitions of extreme daily temperatures and temperature thresholds important in areas such as agriculture or human health. However, for this paper I only examined instances where the daily minimum dips below freezing (0°C). I looked at trends in the number of days below freezing, and in the dates of the first-autumn freeze, last-spring freeze, and the length of the frost-free season (defined as the difference between the last-spring freeze and the first-fall freeze.

In order to examine changes in frost days (days below freezing), I calculated time series of anomalies of the number of frost days for each year and season for each station. I then used each station time series to create an average regional time series using the nine U.S. regions defined in Karl and Knight (1998). Last, I calculated simple linear trends for each regional time series, with the results shown on the maps in Fig. 1. In order to check for autocorrelation problems in the data I used the Durbin-Watson statistic to test time series for first-order autocorrelation; I found there was not a problem.

The regional trends in frost days (Fig. 1a) are consistent with the patterns of mean annual temperature changes shown in Karl et al. (1996). Their analysis showed substantial warming for most of the country, including the western, north-central, and northeastern states, but a general cooling for the southeastern United States. Indeed, the Southeast is one of the relatively few regions of the world that cooled over the twentieth century. Regional changes in the number

DATASET

The data used here come from the U.S. Historical Climatology Network (USHCN) Daily Dataset (Easterling et al. 1999) and comprise daily maximum and minimum temperatures for the 1948–99 period for approximately 1000 Cooperative Observing stations in the contiguous Untied States. The stations in the network were chosen based on both spatial distribution and length of record, and with an eye to minimizing the number of station changes that can cause inhomogeneities. The analysis begins with 1948 due to the lack of earlier data. The National Climatic Data Center (NCDC) did not begin routinely keypunching data until 1948 and only recently has a large-scale effort begun at NCDC to digitize all Cooperative Observer data for the pre-1948 period. These data will be available soon, but will require quality control before the pre-1948 data for the USHCN and the rest of the Cooperative Network are useful for a study such as this one.

Although not explicitly accounted for here, potential problems of homogeneity are worth mentioning. Potential sources of inhomogeneities include station moves, instrument changes, and changing observation times. Since Cooperative Observing stations generally take observations only once per day, changing observation time could affect the number of counts of observations that exceed a given threshold, particularly absolute thresholds such as 0°C. For example, the ideal observation time is midnight, since most maximum temperatures occur in the midafternoon, and most minimum temperatures occur around dawn. Problems of so-called double maxima or double minima arise when the observing time is near either midafternoon or dawn. Since the thermometer is reset near the time when a maximum or minimum occurs one may record that temperature as the maximum or minimum for the observation of the next day. There has been a general trend in the U.S. Cooperative Network to change to a morning observing time in support of hydrologic forecasting needs. This is also true in the USHCN with most observing stations now taking observations at 0700 LST. Although adjustments can be applied to address problems of observation-time bias in monthly data (Karl et al. 1986), these types of adjustments cannot be applied to daily data.

of frost days suggest a similar pattern, with strong decreases in the western and north-central United States. In the northeastern United States annual trends were not statistically significant, but averaged for the country as a whole, a small but significant trend of –0.8 days decade^{-1} is present.

Seasonal trends also show interesting results in Figs. 1b–d, with very little change in the number of days below freezing for the country in the autumn. However, trends for winter and spring show spatial patterns consistent with the annual map. Resulting for spring are also consistent with results found by Groisman et al. (1994) who found a decrease in springtime Northern Hemisphere snow cover coincident with warming spring temperatures.

For the second part of the analysis, I examined changes in dates of the first-autumn and last-spring freezes, and the resulting length of the frost-free season (from the spring date to the fall date). For each year, I found the first-autumn and last-spring freeze dates and converted them to Julian dates. Since some stations could potentially have a freeze date any month of the year, for the purposes of this analysis spring and autumn were arbitrarily divided at 1 July. If a freeze occurred prior to 1 July I assigned it to the spring, and if it occurred on 1 July or later it was assigned to the autumn. Furthermore, if a station had no freeze dates between 1 July and the end of the year, the first freeze date in the next year was assigned to the autumn for that year. Similarly, if a station had no freeze dates between 1 January and 1 July I assigned the last freeze prior to 1 January as the first-spring freeze date. I then created anomaly time series for the first-autumn, the last-spring, and the frost-free season length for all stations in each of the nine regions. Last, I created average anomaly time series from all stations in the region and calculated simple linear trends.

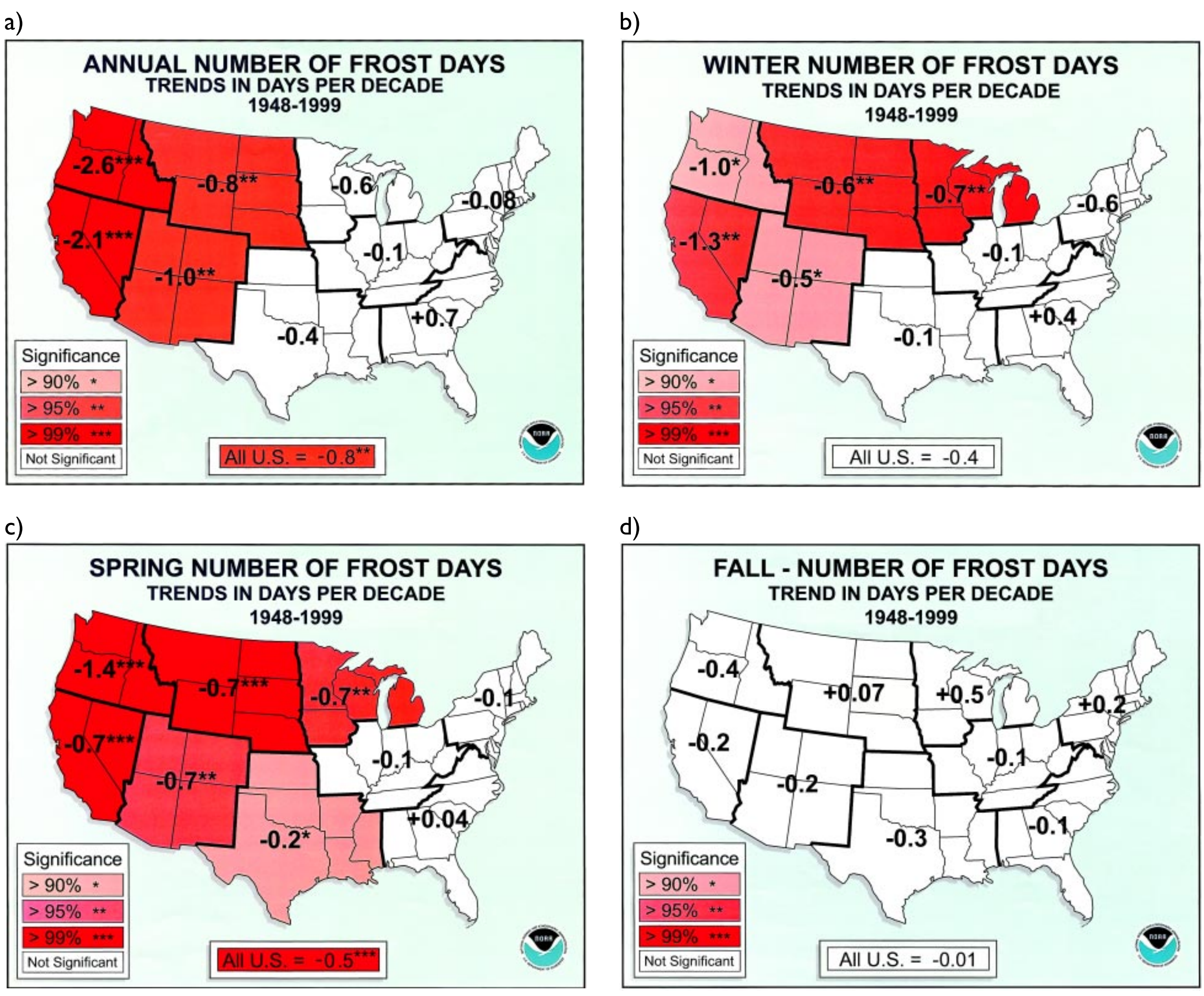
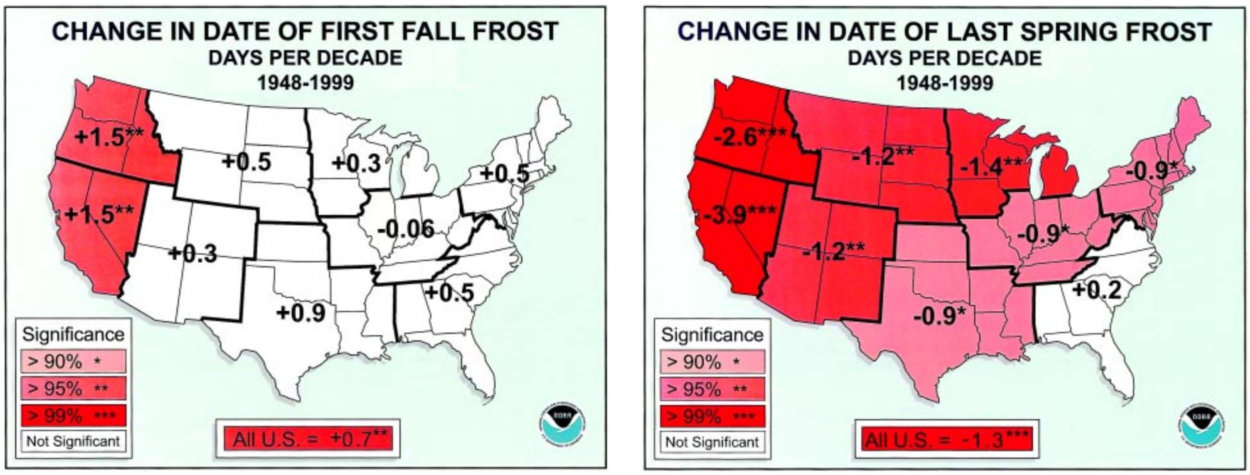


Fig. 1. Trends in number of frost days (days where the min temperature was below 0°C) in days decade^{-1} for (a) annual, (b) winter, (c) spring, and (d) fall.

a) b)



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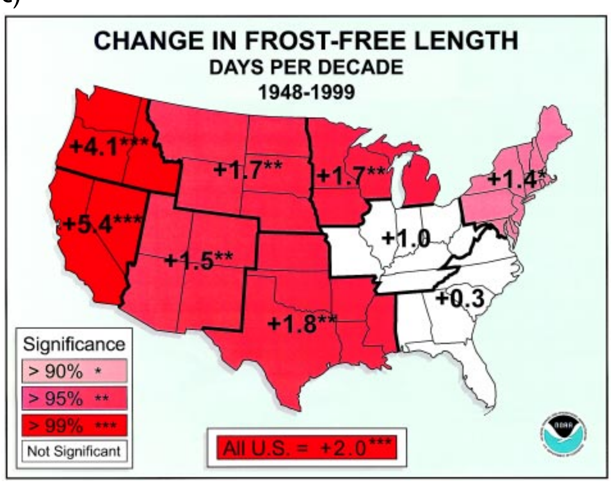

Fig. 2. Trends in the average date for the (a) first-fall frost (where min temperature was below 0°C), (b) last-spring frost, and (c) the frost-free season. Trends are in days decade^{-1}.

The results shown in Fig. 2 are also consistent with patterns of warming for the annual average temperatures for the United States. Although statistically significant changes in the first-autumn frost occur only in the West Coast area, there is a significant change to a later first-autumn frost when averages across the entire country. Changes in the date of the last-spring freeze are consistent with results for changes in the number of spring frost days. Except for the Southeast, which shows a slight move to a later date, the last-spring frost is getting earlier, and a shift of about −1.3 days decade^{-1} occurs for the whole country. For the frost-free season, results are also consistent with those presented earlier, with trend to an increasing frost-free season length, but the change is small in the central and southeastern states. Averaged for the United States as a whole, the frost-free season length is increasing about 2 days decade^{-1}.

Shifts in observation times may affect the results of this analysis (see the sidebar). In the U.S. Historical Climatology Network (USHCN) many stations have changed to morning observation times and observations at for instance, 0700 local time, are close to the expected time for the minimum temperature to be reached. The observer takes a reading, then resets the instruments, and if the temperature the next morning is not as cold then the minimum temperature reading would be the same as when the instrument was reset the previous morning. This is a "double minima" that would affect counts of days of how many minima exceed an absolute threshold, such as 0°C. Similar double maxima can bias trends in maximum temperature when the station has an afternoon observing time. Might this potentially affect the results presented here? A switch from an afternoon observation time to a morning observing time would likely increase the number of days below freezing relative to the station that continues to use an afternoon observer. Since the United States as a whole, and most regions have had fewer frost days, and an earlier last-spring freeze, then the results presented here would likely be enhanced if stations had maintained a constant observing time throughout the analysis period.

To get a clear overall impression of these changes discussed above, consider the time series for the northern plains region in Fig. 3. This shows strong warming in the minimum temperature, a significant reduction in the number of days below freezing, and a lengthening of the frost-free season over the 1948–99 period. Clearly, when annual minimum temperature is higher, frost days are reduced and the frost-

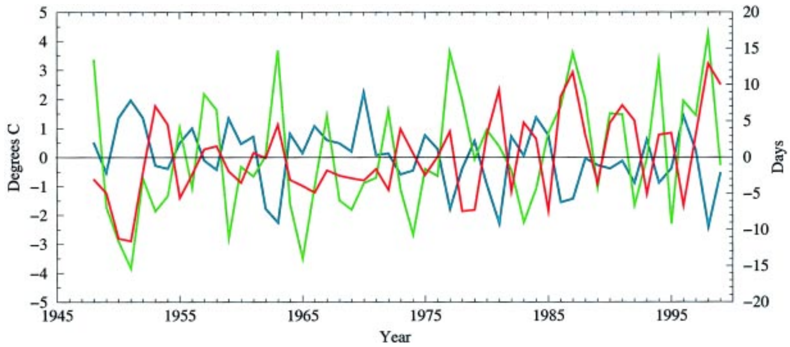

Fig. 3. Time series of annual minimum temperature (bright red), growing seasonal length (green), and number of frost days (blue) for the northern plains region.

free season is longer. Similarly, when temperatures are colder, the opposite is true.

CONCLUSIONS. One of the changes expected with an increase in surface temperature is a change in what are currently considered extreme temperatures, both hot and cold extremes. The results here are consistent with what would be expected based on previous analyses of annual temperature trends and changes in frost days for specific regions. Results here, particularly for changes in the last-spring freeze and frost-free season length, are regionally consistent with those found by Cooter and LeDuc (1995), DeGaetano (1996), Schwartz and Reiter (2000), and Cayan et al. (2001). However, the southeastern United States, which has shown a cooling trend in annual temperatures over the twentieth century in previous analyses, shows no changes in either the number of frost days or changes in the frost-free season. Indeed, an analysis of the annual minimum temperature using USHCN (see Easterling et al. 1996) homogeneity and urban-adjusted data for the southeastern United States, as defined here and performed for the 1948–99 period, reveled no statistically significant trend.

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